

## Optical Phased Array Antennas Using Coupled Vertical Cavity Surface Emitting Lasers

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High data rate communication links are needed to meet the needs of NASA as well as other organizations to develop space-based optical communication systems. These systems must be robust to high radiation environments, reliable, and operate over a wide temperature range. Highly desirable features include beam steering capability, reconfigurability, low power consumption, and small aperture size. Optical communication links, using coupled vertical cavity emitting laser radiating elements, are promising candidates for the transmit portion of these communication links. In this talk we describe a mission scenario, and how the antenna requirements are derived from the mission needs. We describe a potential architecture for this type of antenna, and outline the advantages and drawbacks of this approach relative to competing technologies.

The technology we are proposing uses coupled arrays of 1550 nm vertical cavity surface emitting lasers for transmission. The feasibility of coupling these arrays together, to form coherent high-power beams that can be modulated at data rates exceeding 1 Gbps, will be explored. We will propose an architecture that enables electronic beam steering, thus mitigating the need for ancillary acquisition, tracking and beam pointing equipment such as needed for current optical communication systems. The beam-steering capability we are proposing also opens the possibility of using this technology for inter-satellite communication links, and satellite-to-surface links.

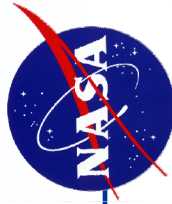
**Keywords:** *Coupled Oscillator, Optical Antenna, VCSEL*

Oral presentation preferred

# Optical Phased Array Antennas Using Coupled Vertical Cavity Surface Emitting Lasers

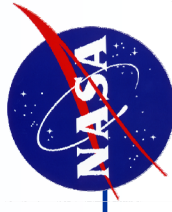
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Nessel,<sup>3</sup> and Félix A. Miranda<sup>3</sup>

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# Objectives

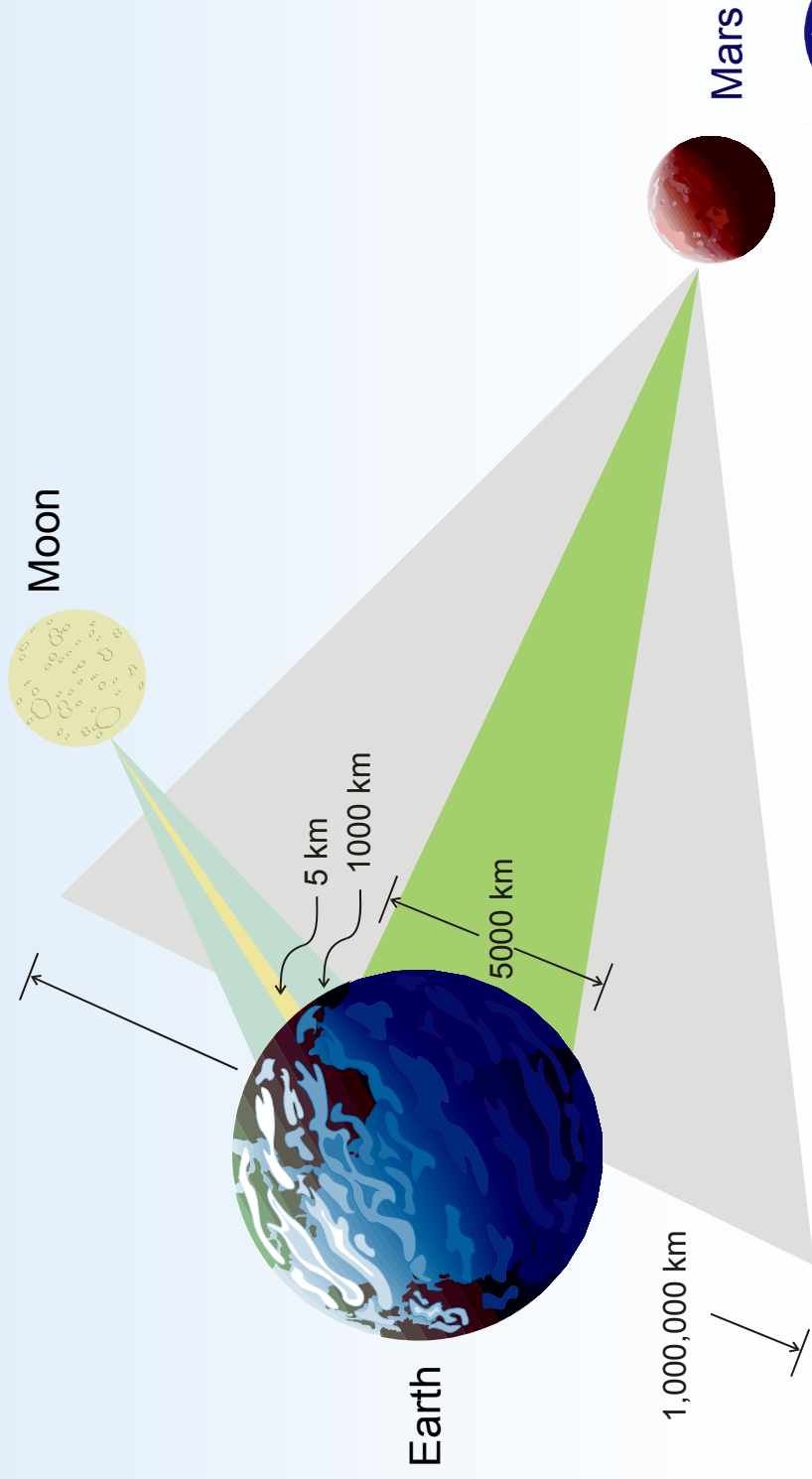
- VCSELs that emit at 1.3 and 1.55  $\mu\text{m}$  are attractive low-cost sources for high-speed fiber optic communication systems because of their low operating current, high-speed modulation.
- The key objective of this study is to discern future needs of laser communication systems, evaluate existing and emerging technologies, and propose a research program to develop communication systems tailored to meet NASA's needs.
  - High power laser sources, so as to provide high data rates
    - Gbps for satellite networks and links as far as Earth-to-Lunar
    - 100 Mbps for Earth-to-Mars communication links
  - High power laser source enables smaller diameter transmit aperture, which mitigating the pointing and tracking difficulties.



# Shorter wavelength enabled by optical antenna reduces beam size at the Earth's surface

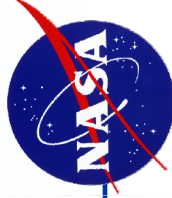
Compare beam sizes at Earth's surface, assuming:

- a) 1550 nanometer wavelength optical link, with a 10 cm transmit aperture;
- b) 30 GHz (= 1 cm wavelength) microwave link, with a 4 meter aperture.



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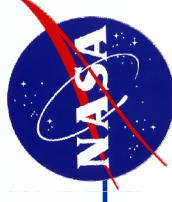
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# Space-Based Optical Communication Demonstrations

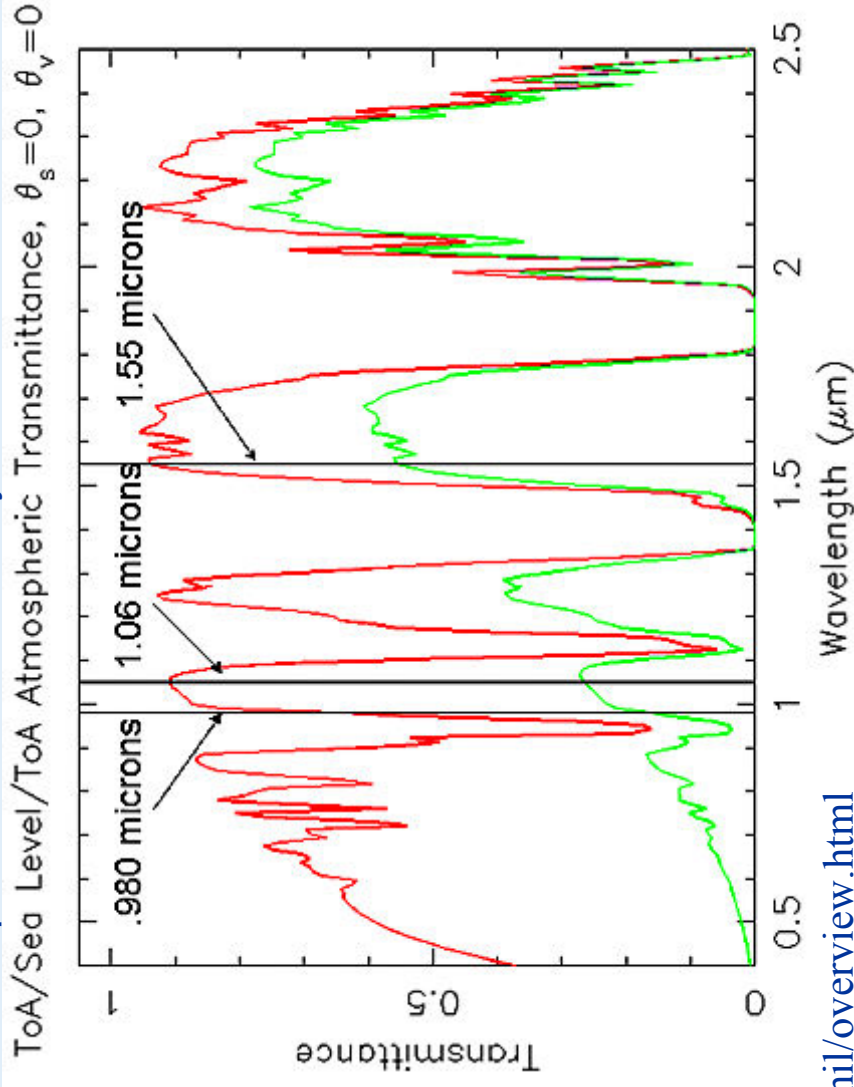
Sponsor	Year	Summary
Japanese Aerospace Exploration Agency	2006	Bi-directional communication from a LEO satellite (orbital velocity = 7 km/sec) to a ground station.
Laser Utilizing Communications Satellite (ESA/JAXA)	2005	50 megabits per second data rate from Kirari (LEO) satellite to ground station, and 2 megabits per second from Kirari to Artemis (GEO) satellite.
Capanina (European/Japanese Consortium)	2005	1.25 gigabits per second downlink from stratosphere to ground station. Maximum link distance was 64 km, and negligible transmission loss was observed.
UAV Downlink Demonstration (NASA/JPL)	2002	Up to 2.5 gigabits per second downlink from a plane and a UAV to ground station.
Semiconductor Inter-Satellite Link Experiment (ESA)	2001	Up to 450 megabits per second data link between two GEO satellites (SPOT4 and Artemis), spaced thousands of km apart.
Ground-to-Orbit Laser-Com Demonstration (NASA/JPL)	1995	Bi-directional communication from GEO satellite (ETS-6) to ground station. Data rate was 1 megabit per second.
Galileo Optical Experiment (NASA/JPL)	1992	Laser uplink detected at a distance of $6 \times 10^5$ km

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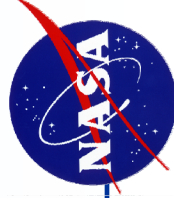


# 1550 nm offers superior transmittance under non-ideal atmospheric conditions

- More robust communication links
- Problems caused by attenuation, scintillation and fading are less severe than at shorter wavelengths.
- Detectors operate at quantum level sensitivity.



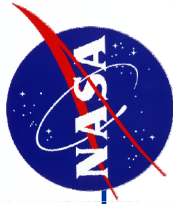
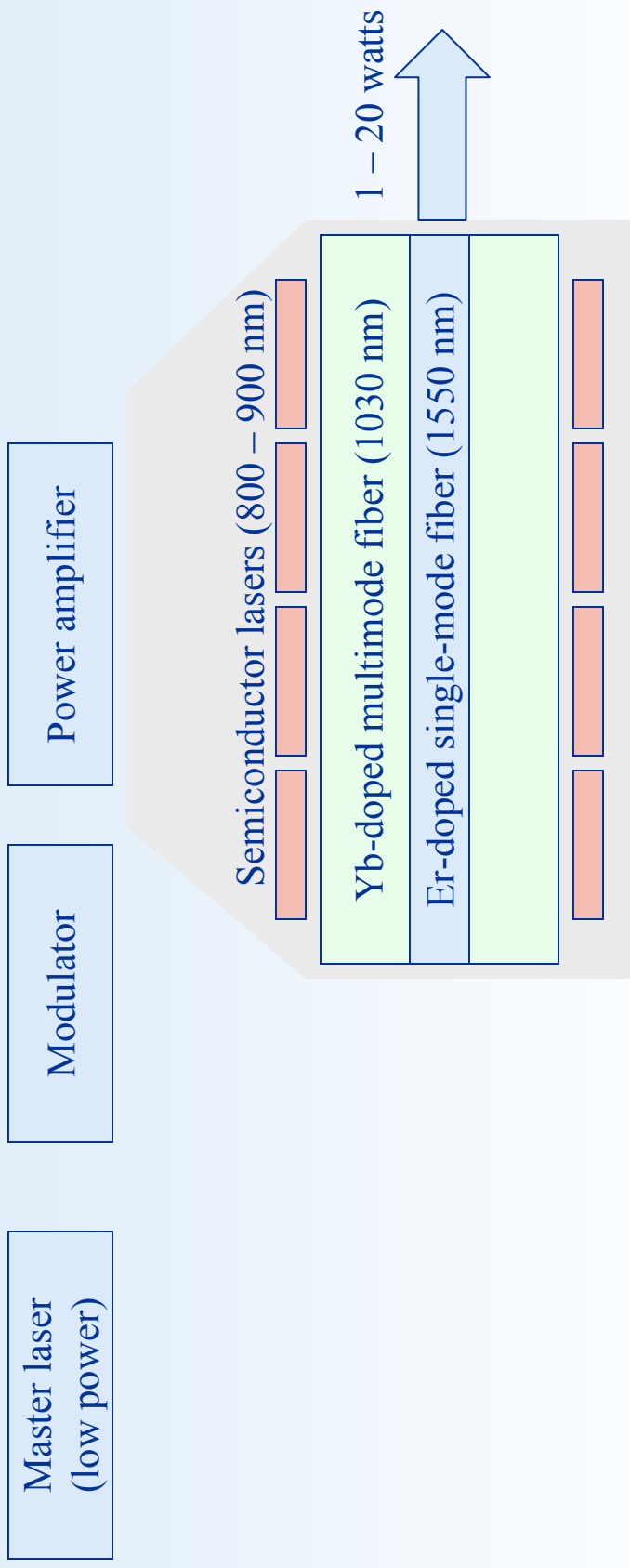
<http://mrr.nrl.navy.mil/overview.html>



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# Conventional architecture for transmit subsystem

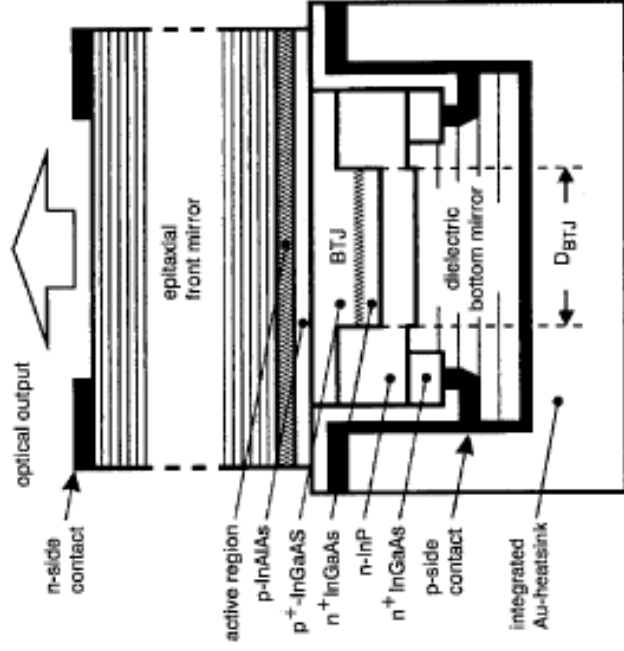


# Advances in long-wavelength VCSEL development suggest that high power transmitters may be feasible

Output power = 7 mW at 20 °C

Aperture size = 20  $\mu\text{m}$

Wavelength = 1.55  $\mu\text{m}$

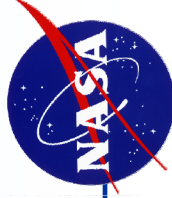


*An array with a VCSEL linear spacing of 100  $\mu\text{m}$  corresponds to 10,000 elements per  $\text{cm}^2$ .*

*If each element radiates 7 mW, the total power output from A 1  $\text{cm}^2$  aperture is 70 watts.*

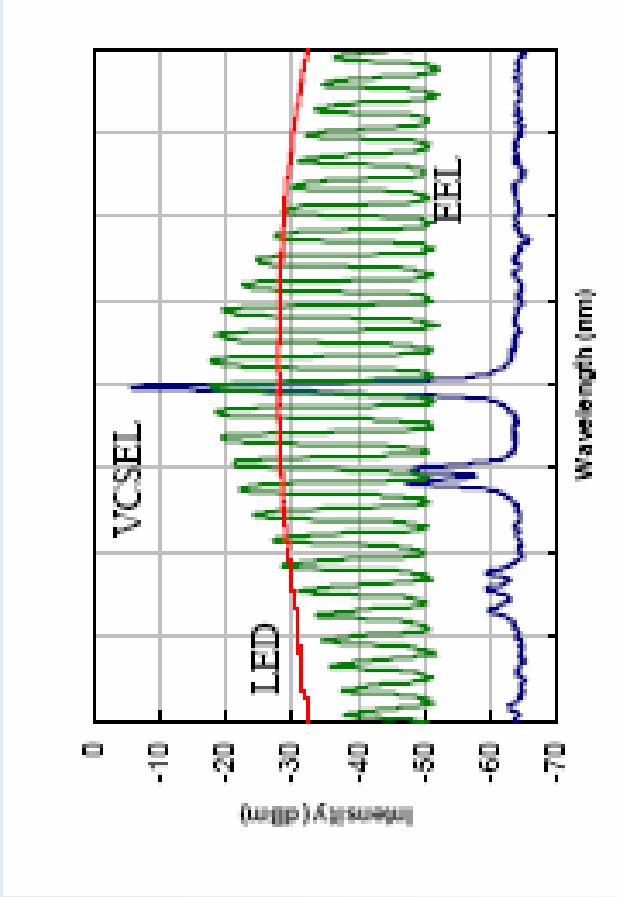
Structure of 1.55  $\mu\text{m}$  InP-based VCSEL  
(from R. Shau et al., *Electronics Letters* 37, p. 1295 (2001)).

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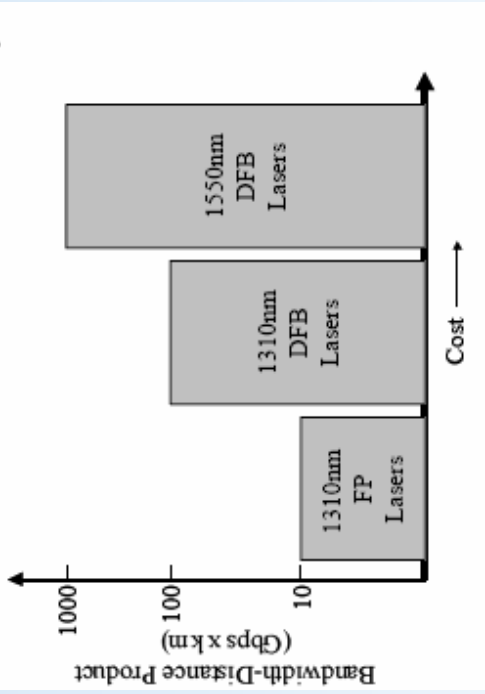




1550 nm VCSEL arrays are attractive for high bandwidth, long-distance optical communications



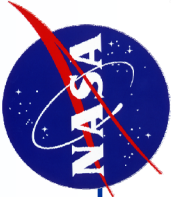
Optical spectra of a VCSEL, LED, and edge emitting laser



Attribute	Symbol	Units	SM VCSEL	MM VCSEL	EE Laser	LED
Electrical Power	$P_{elec}$	mW	5	20	60	60
Optical Power	$P_{opt}$	mW	1	5	10	1
Efficiency at $P_{opt}=1mW$	$\eta$	%	20	10	5	2*
Wavelength	$\lambda$	nm	760-860	670-870	630-1300	400-1300
Spectral Width	$\Delta\lambda$	nm	0.01	0.5	2	50
Spectral Tuning (Temperature)	$\Delta\lambda/\Delta T$	nm/°C	0.06	0.06	0.3	0.3
Spectral Tuning (Current)	$\Delta\lambda/\Delta I$	nm/mA	0.25	0.09		
Beam Angle (full width at half of maximum value)	$\angle$	°	<15	~15	15 par. 35 perp	120

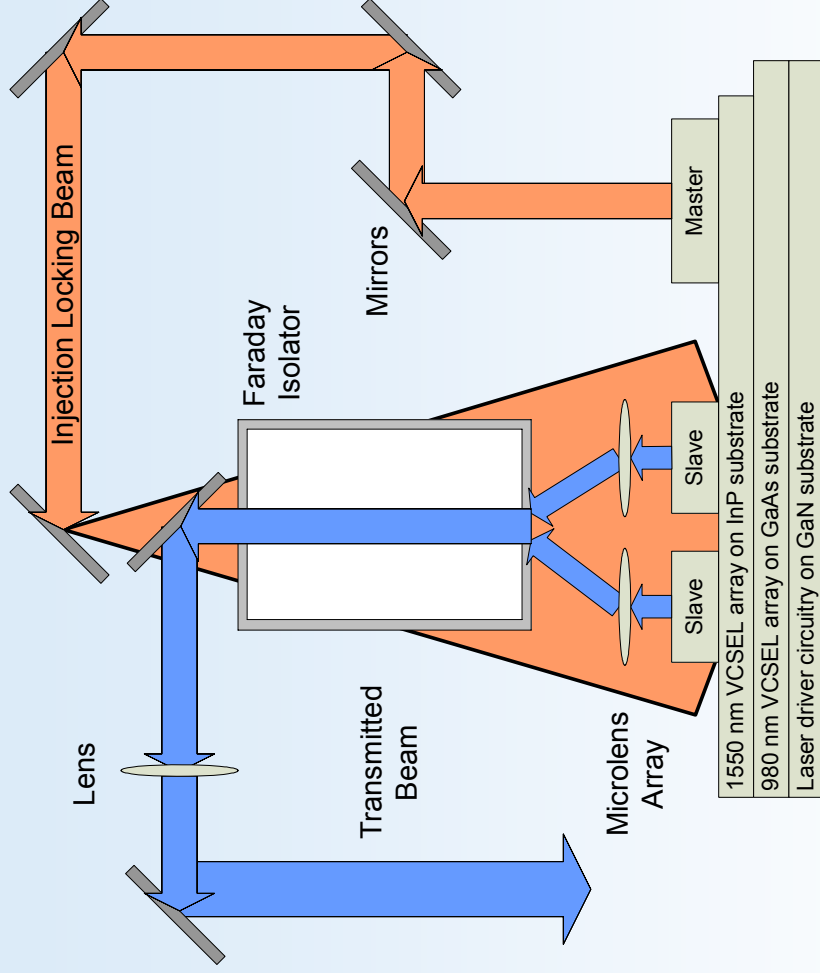
J.A. Tatum and J.K. Guenter, “The VCSELs are Coming,” <http://www.advancedopticalcomponents.com>

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# Coherent emission achieved by injection locking

## VCSEL elements



$$-k_c \sqrt{\frac{S_{inj}}{S}} \sqrt{1 + \alpha^2} < \Delta\omega < k_c \sqrt{\frac{S_{inj}}{S}}$$

$k_c$  = coupling coefficient between the master into the slave VCSELs,

$S_{inj}$  = the injected photon number,

$S$  = photon number inside the VCSEL cavity,

$\alpha$  = linewidth enhancement factor,

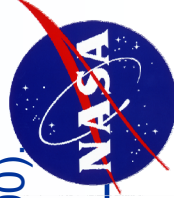
$\Delta\omega$  = detuning between the master and slave lasers  
( $=\omega_{master} - \omega_{slave}$ )

Concept for a high power long-wavelength 1550 nm VCSEL with coherent emission, based on optical pumping from a 2-D array of high power incoherent 980 nm VCSELs.

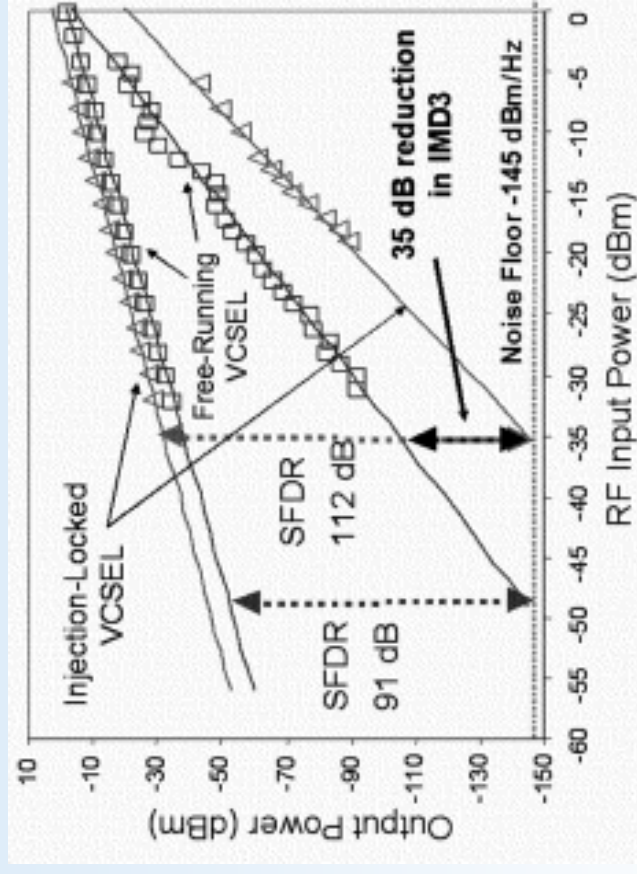
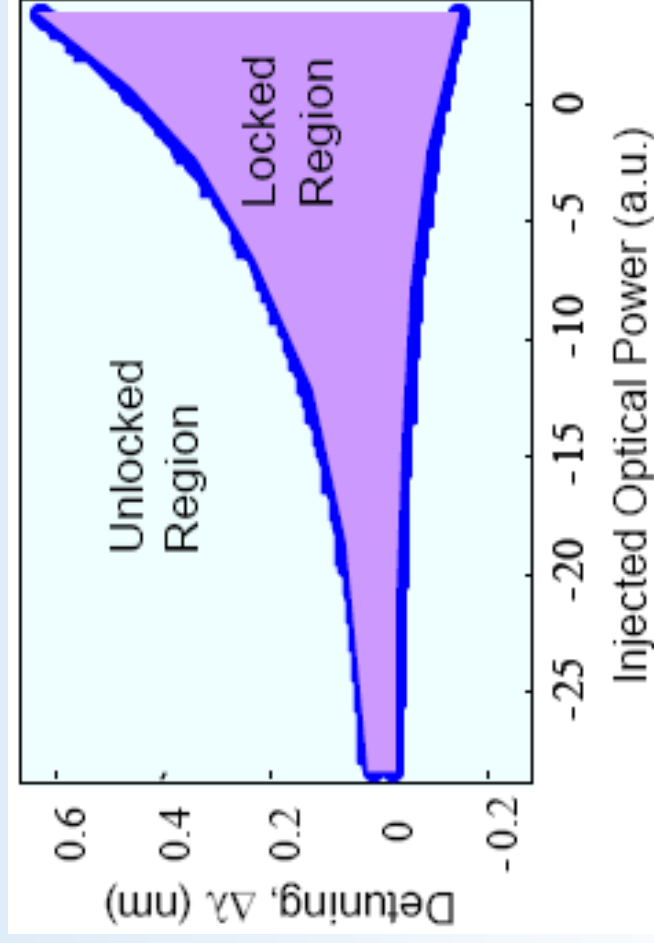
Some elements of concept taken from B. Lücke et al. "Autostable injection-locking of a 4x4 VCSEL array with an on-chip master laser," Proc. SPIE 3946, p. 240 - 245 (2000).

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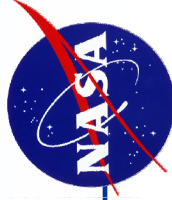


## Injection locking improves spur-free dynamic range

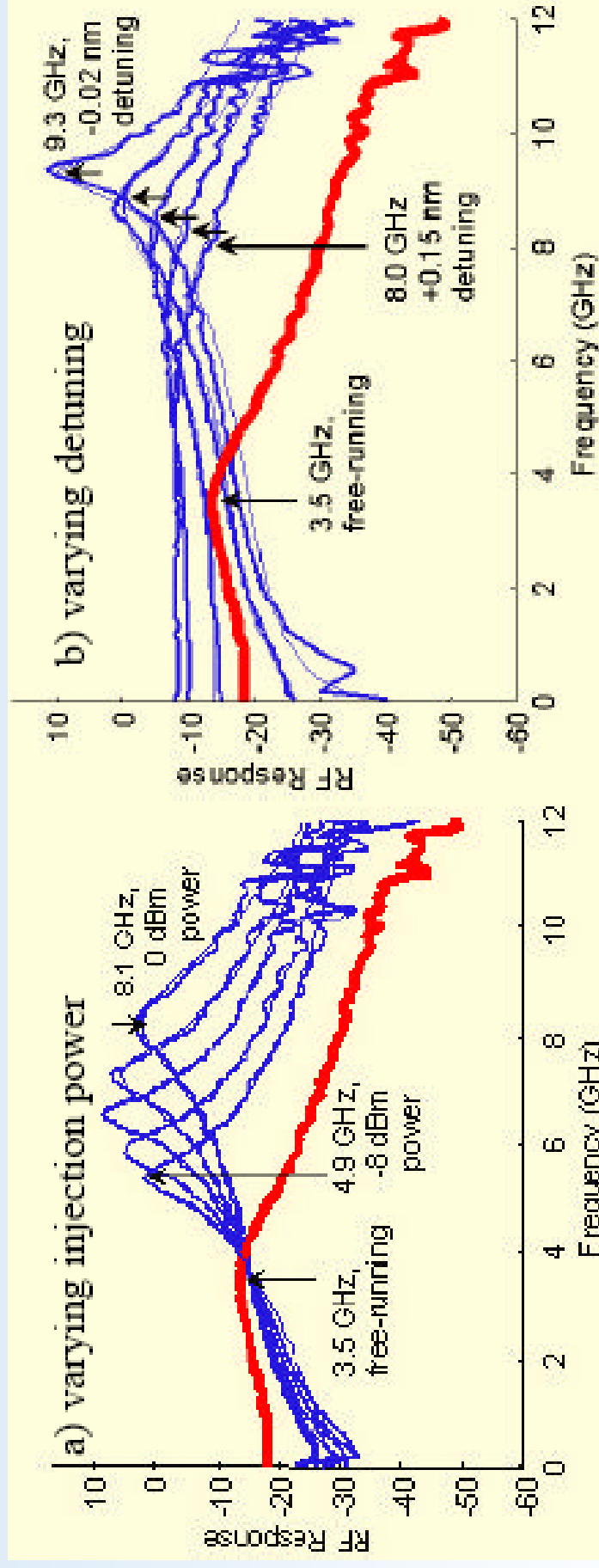


C-H Chang, L. Chrostowski, and C.J. Chang-Hasnain, "Injection Locking of VCSELs," *IEEE J. Selected Topics in Quantum Electronics* 9, p. 1386-1393 (2003).

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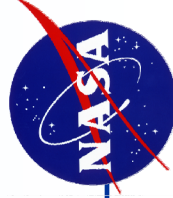


## Injection locking improves frequency response of VCSEL array, thus extending the bandwidth

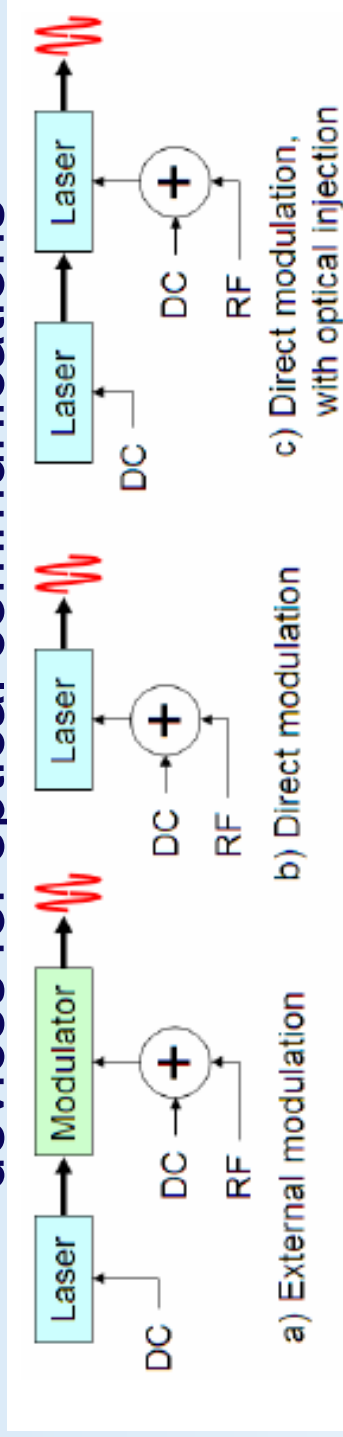


C-H Chang, L. Chrostowski, and C.J. Chang-Hasnain, "Injection Locking of VCSELs," *IEEE J. Selected Topics in Quantum Electronics* 9, p. 1386-1393 (2003).

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# Injection locking improves performance of VCSEL devices for optical communications



## Advantages

- High linearity
- High optical power
- Low chirp
- Low noise

## Disadvantages

- High power consumption
- High cost

## Advantages

- Low cost

## Disadvantages

- Limited frequency response
- High nonlinearity
- High noise
- High chirp

## Advantages

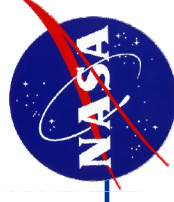
- Good RF bandwidth
- Good linearity
- Low noise
- Low chirp
- Low power consumption
- Low cost

## Disadvantages

- Performance is not as good as externally modulated system

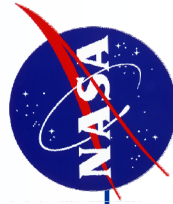
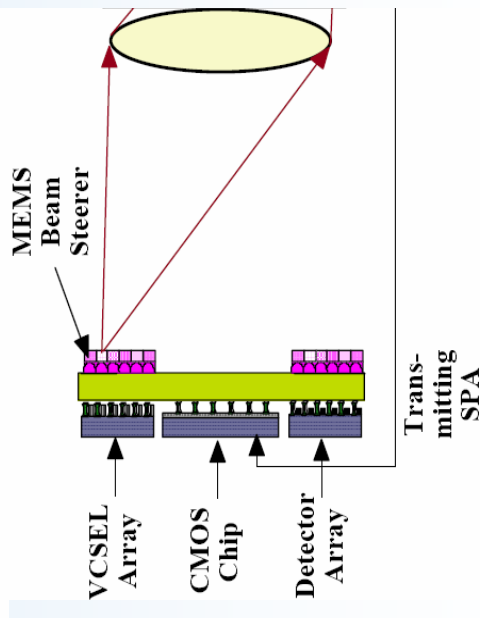
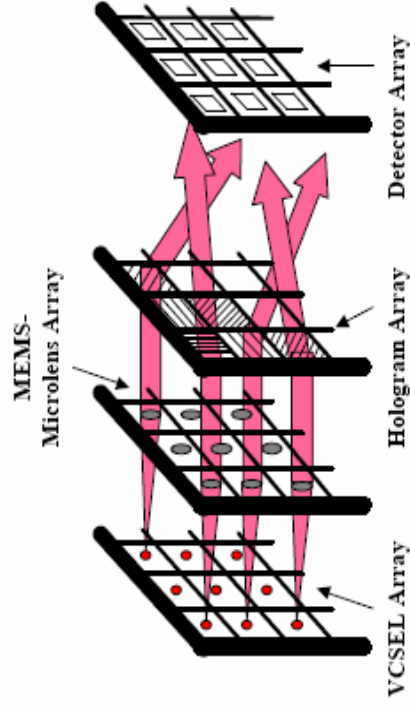
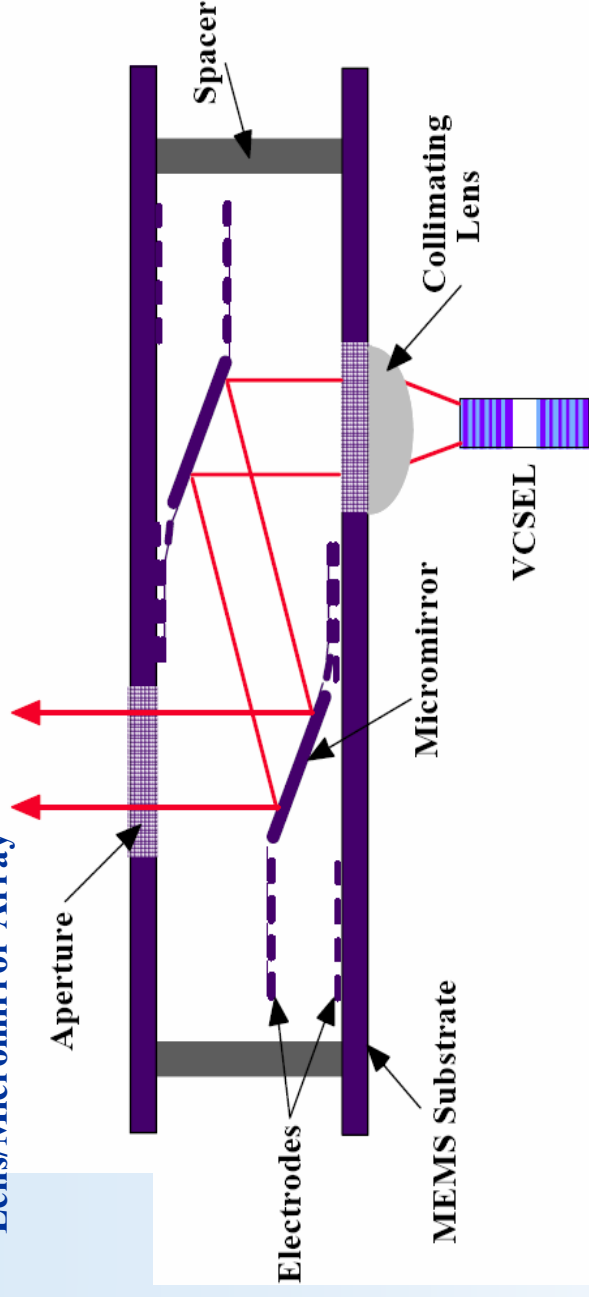
From "Optical Injection Locking of Vertical Cavity Surface Emitting Lasers," by Lukas Chrostowski (Ph. D. Thesis, Univ. of California-Berkely, 2003)

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# VCSEL Array Architectures

Lens/Micromirror Array

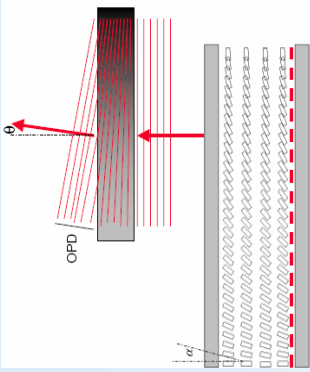


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# Beam-Steering Technology

Integrated Beam Router



Max. Steering Angle:  $\pm 5^\circ$

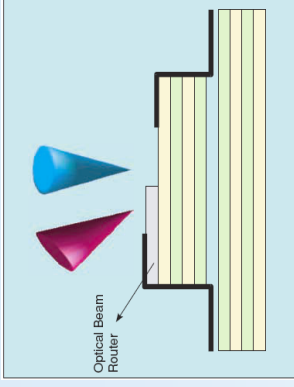
Max. Steering Speed: 10 kHz

## Advantages:

- Does not rely on mechanical motion

## Disadvantages:

- Suffers from fringing fields
- Existence of flyback region



Max. Beam Deflection:  $\pm 3^\circ$

Max. Steering Speed: 2 GHz

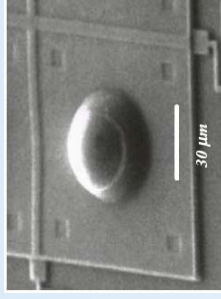
## Advantages:

- No mechanical motion  
(based on *current injection*)
- Direct integration with VCSEL

## Disadvantages:

- Large crosstalk components

MicroOptoElectroMechanical Systems (MOEMS)



Microlens

Max. Steering Angle:  $\pm 2^\circ$

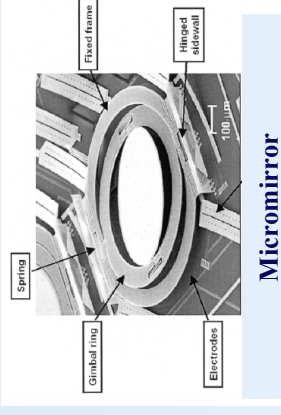
Max. Steering Speed: 1 kHz

## Advantages:

- Only micromotion necessary
- 2D/3D beam steering possible
- No diffraction loss

## Disadvantages:

- Relies on mechanical motion  
(*vibration sensitive*)
- Slow speeds
- Difficult fabrication



Micromirror

Max. Beam Deflection:  $\pm 3^\circ$

Max. Steering Speed: < 1 kHz

## Advantages:

- Only micromotion necessary
- Precise focus length

## Disadvantages:

- Relies on mechanical motion  
(*vibration sensitive*)
- Slow speeds
- Snap-down effect

Implementing a combination of the above with lenses, gratings, or holographic arrays has demonstrated improved performance, in terms of maximum beam-steering angles.



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# Conclusions

- Optical communications offer significant benefits in terms of data rate capability and antenna aperture size, as compared to RF communication systems.
  - Data links over vast distances
  - Multi-gigabit satellite networks
- VCSEL transmit antennas operating at 1550 nm are an attractive choice for transmit antennas.
  - High efficiency
  - High transmit power, thus minimizing the need for large aperture antennas
    - Reduces demands on acquisition, pointing, and tracking systems
  - Coupled oscillator approach increases the antenna gain and maximum frequency at which the array can be modulated, thus increasing the permissible data rates.

